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An Approximate Correlation for Determining Liner Failure Criteria in the Prestressed Concrete Containment Vessel

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1. Introduction

Liner plate attached inside the prestressed concrete containment vessel (PCCV) is a key component to prevent the leakage of the radioactive materials [1,2]. Thus, understanding the failure criteria of the liner is crucial for accurate evaluation of the structural integrity of PCCV [1]. However, existing approach to determine liner failure criteria has a limitation to consider ambiguous or various free-field regions and material properties of the liner [1].

In this paper, a recently proposed approximate correlation with conservative factors was summarized by taking into account the expanded free-field ranges and material properties to determine realistic failure criteria for liner. To demonstrate the applicability of the suggested correlation, the internal pressure capacities of full-scale containment buildings, such as APR-1400 and CPR-1000 [3,4], at liner failure were evaluated and compared using liner failure criteria according to RG 1.216 [5] and an approximate correlation [1].

2. Modification for Approximate Correlation

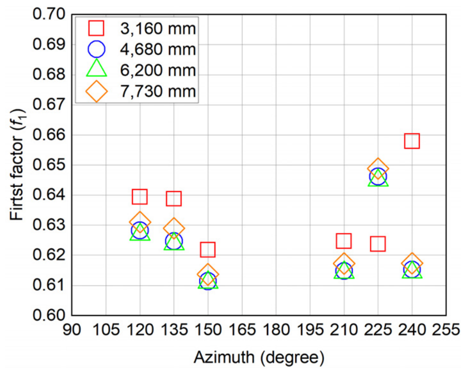
An approximate correlation based on the findings of Cherry and Smith [6] was modified and suggested by considering conservative factors, such as the tri-axial stress state, convergence of the finite element (FE) model, material property uncertainties, and corrosion degradation [1]. By incorporating the expanded free-field regions and specific material properties of each containment type, the modified correlation enhanced the accuracy and reliability of liner failure predictions in PCCVs [1]. The approximate correlation is given as follows:

(1) $\varepsilon_{(failure)_m} = \varepsilon_{ultimate} \times (f_1)_m \times (f_2)_m \times f_3 \times f_4 \times \alpha$

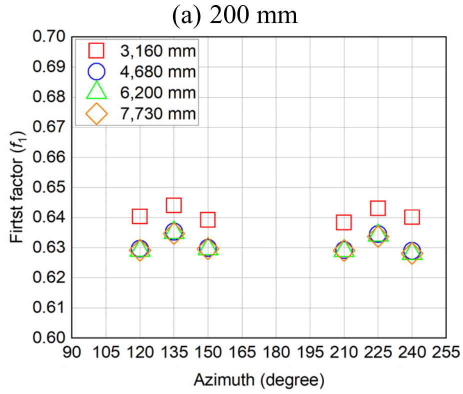
where $\varepsilon_{ultimate}$ is the ultimate strain of the liner, $(f_1)_m$ is the modified first factor to determine the relationship between the triaxial stress state and the failure strain, $(f_2)_m$ is the modified second factor to account for the convergence of the FE model, f_3 is the third factor accounting for material property uncertainties, f_4 is the fourth factor accounting for the level of corrosion degradation, α is the correction factor to adjust the prediction results to experimental data [1].

Based on the distribution of first factors calculated by $f_1 = 1.648 * e^{-(\sigma_1+\sigma_2+\sigma_3)/2\sigma_{von}}$, it was conservatively assumed that the modified first factor, $(f_1)_m$ within expanded free-field ranges will be 0.658, which is the average value from the distribution of all the calculated f_1 [1]. Derived from numerical findings, Fig. 1 demonstrates the distributions of the calculated first factors within the expanded free-field ranges for four mesh sizes (200, 300, 400, and 500 mm) [1].

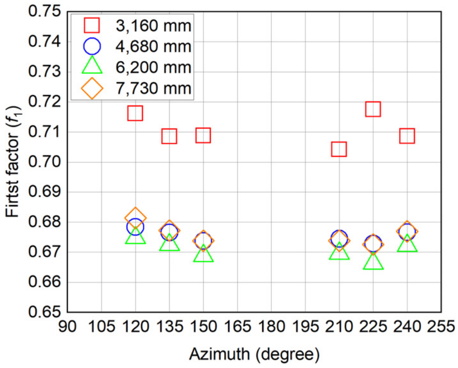
The convergence of the FE modeling, which is used to assess the mesh sensitivity, is generally denoted by the second factor, $(f_2)_m$. In this study, the modified second factor $(f_2)_m$ was suggested using the coefficient of variation of the liner's principal strain over expanded free-field ranges [1]. Details of the principal strain distributions of the liner for four different mesh sizes for the modified second factor can be found in Cho et al. [1]. The values were 0.073, 0.122, and 0.181 for the minimum, average, and maximum. The best estimate, upper limit, and lower limit were conservatively estimated to be 0.07, 0.11, and 0.18, respectively [1].



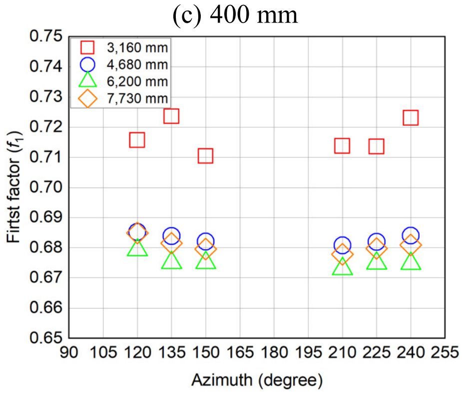
(a) 200 mm



(b) 300 mm



(c) 400 mm



(d) 500 mm

(e)

Fig. 1. Distribution of the calculated first factor, f_1 in the expanded free-field ranges according to different mesh sizes [1].

The most significant variation in the range of material properties was found in elongation, which varied by 22% from the mean in a normal distribution [1,6]. Thus, 0.78, 1.00, and 1.22 were found to be the lower limit, best estimate, and upper limit constants for f_3 [1,6]. Cherry and Smith considered that the fourth factor, f_4, represented the degree of corrosion degradation [6]. The lower limit, best estimate and upper limit constants were determined to be 0.25, 0.5, and 0.75, respectively [1,6].

As listed in Table 1, the correction factor, α was used to modify the predicted results through a rough correlation to the experimental data on liner failure collected by Hessheimer et al. [1] as follows:

(2) $\alpha = \varepsilon_{failure(test)} / \varepsilon_{failure(prediction)}$

where $\varepsilon_{failure(test)}$ represents the global free-field strain of liner, which is defined as the ratio of the measured radial displacement, $\varepsilon_{failure(prediction)}$ is equal to $\varepsilon_{ultimate} \times (f_1)_m \times (f_2)_m \times f_3 \times f_4$ where $\varepsilon_{ultimate}$ is 0.35 according to Hessheimer et al. [1,6]. As indicated in Table 2, the minimum, median, and maximum values of the correction factors in the columns for the lower limit, best estimate and upper limit were conservatively estimated to be 0.80, 0.26, and 0.11, respectively [1]. Table 2 represents the summary of conservative factors of the lower limit, best estimate and upper limit for the approximate correlation [1].

Table 1. Distribution of the correction factor, α for approximate correlation [1]

Azimuth (degree)	Elevation (mm)	Test[1)]	α[2)]		
			Lower limit	Best estimate	Upper limit
120	4680	0.0034	1.08	0.27	0.09
135	2630	0.0025	0.80	0.20	0.07
	4680	0.0033	1.05	0.26	0.09
	6200	0.0035	1.11	0.28	0.09
	7730	0.0038	1.21	0.30	0.10
210	4680	0.0033	1.05	0.26	0.09
240	4680	0.0033	1.05	0.26	0.09
	7730	0.0041	1.30	0.32	0.11

1) Global free-field strain from Hessheimer et al. [7].
2) $\varepsilon_{failure(prediction)} = \varepsilon_{ultimate} \times (f_1)_m \times (f_2)_m \times f_3 \times f_4$ where $\varepsilon_{ultimate} = 0.35$.

Table 2. Summary of conservative factors for the approximate correlation [1]

Factor	Lower limit	Best estimate	Upper limit
$(f_1)_m$	0.658	0.658	0.658
$(f_2)_m$	0.07	0.11	0.18
f_3*	0.78	1.00	1.22
f_4*	0.25	0.50	0.75
α	0.80	0.26	0.11
$\varepsilon_{(failure)_m}$	0.0071 × $\varepsilon_{ultimate}$	0.0096 × $\varepsilon_{ultimate}$	0.0117 × $\varepsilon_{ultimate}$

* f_3 and f_4 refer to Cherry and Smith's findings [6].

3. Applicability of the Approximate Correlation

To evaluate the accuracy and reliability of the approximate correlation for predicting liner failure [1], two specific types of containment buildings, such as APR-1400 and CPR-1000 [3,4], were taken into account. The ultimate liner strains in each containment structure were 25% (SA-516 Grade 60) for APR-1400 [3] and 22% (P265GH) for CPR-1000 [4].

Using the same factors as shown in Table 2, the best estimates of the liner failure strain were determined to be 0.24% for APR-1400 and 0.21 % for CPR-1000 [1]. Table 3 provides examples of liner failure strain prediction in full-scale containment structures, such as the APR-1400 and CPR-1000 [1]. The failure strains for APR-1400 and CPR-1000 were predicted by Alhanaee et al. [3] and Jin et al. [4], respectively. They utilized RG 1.216 to assess the liner failure and evaluate the internal pressure capacities of containment structures [3,4].

Table 3. Best estimate of failure in a liner from approximate correlation for full-scale containments [1]

Containment type	Liner material	$\varepsilon_{(failure)_m}$		
		Lower limit	Best estimate	Upper limit
APR-1400 [3]	$\varepsilon_{ultimate}$= 0.25 (SA-516 Grade 60)	0.0018 (0.18 %)	0.0024 (0.24 %)	0.0030 (0.30 %)
CPR-1000 [4]	$\varepsilon_{ultimate}$=0.22 (P265GH)	0.0016 (0.16 %)	0.0021 (0.21 %)	0.0026 (0.26 %)

As depicted in Fig. 2, the internal pressure capacity of the APR-1400 containment building was determined to be 939.6 kPa based on the liner failure criteria of 0.4% in RG 1.216 [1]. Using the best estimate liner failure criteria of 0.24%, the proposed correlation predicted that the APR-1400 containment building's internal pressure capacity will be 869.1 kPa, which shows a difference of 7.5% [1]. Fig. 3 describes that the internal pressure capacity of the CPR-1000 nuclear containment building was calculated to be 948.0 kPa using the liner failure criteria of 0.4% in RG 1.216, but it was predicted that it will be 807.1 kPa using the best estimate liner failure criteria of 0.21% by the proposed correlation, representing a difference of 14.9% [1].

For both containment structures, internal pressure capacities predicted by the quick and approximate correlation for best estimate liner failure criteria were lower than those estimated by Alhanaee et al. [3] and Jin et al. [4].

4. Conclusion

This study introduced an approximate correlation to determine liner failure criteria of PCCV, an essential aspect of nuclear safety. The suggested approach incorporated important factors, such as changes to the triaxial stress state, convergence of the FE model, material property uncertainties, and corrosion degradation. In order to improve the prediction accuracy and reliability, it also takes into account expanded free-field regions and specific material properties of various kinds of containment. Two representative containment buildings of the APR-1400 and CPR-1000 were utilized to demonstrate the effectiveness of the suggested correlation. Finally, the approximate correlation revealed conservative estimates of the internal pressure capacities compared to conventional failure criteria of RG 1.216. The study will provide a robust method for enhancing the nuclear power plant containment structure safety assessment.

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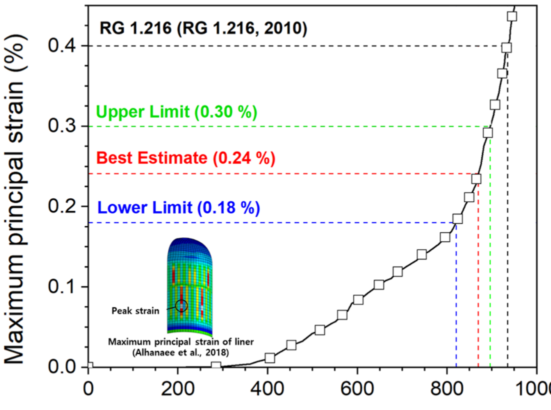

Fig. 2. Internal pressure capacities of APR-1400 [1]

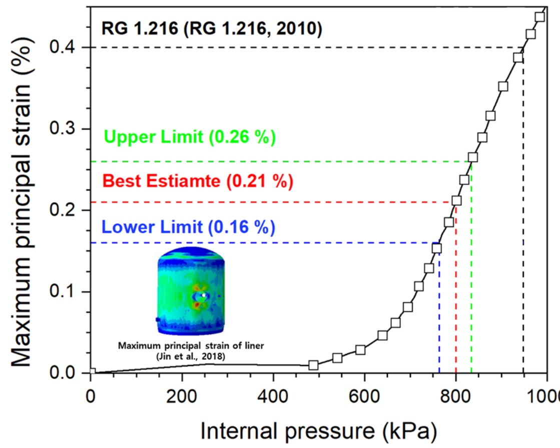

Fig. 3. Internal pressure capacities of CPR-1000 [1]

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